Low-Frequency Radio Astronomical Connections to Quarks and the Cosmos

A Perspective from the LOFAR Community

Executive Summary

The Low Frequency Array (LOFAR) will be a next-generation radio telescope operating below 250 MHz that will provide answers to several of the eleven questions about fundamental physics posed in the National Academy of Sciences report, *Connecting Quarks with the Cosmos*.

How Do Cosmic Accelerators Work and What Are They Accelerating? LOFAR will detect radio pulses from the impact of ultra-high energy particles on the Earth's atmosphere and potentially from the impact of ultra-high energy neutrinos on the lunar regolith. Expected detection rates for cosmic ray impacts on the atmosphere at or above the Greisen-Zatsepin-Kuzmin (GZK) limit are tens per year, owing to the distributed nature of the array and its near-omnidirectional antennas, yielding significant information on the extremes of cosmic acceleration.

What is Dark Matter? What is Dark Energy? A key LOFAR project is the detection of the redshifted hyperfine transition from hydrogen at and prior to the epoch of reionization. It will probe the formation of the first structures, including the distribution and properties of dark matter responsible for forming these first structures, and potentially probe to a time before any stars had formed. Through comparison to the size of structures at low redshifts, these measurements will also constrain the equation of state of dark energy,

LOFAR may play an important, though not central, role in answering additional questions:

Are There Additional Space-Time Dimensions? LOFAR will enable searches for variations in fundamental constants to large redshifts.

LOFAR will also detect a large number of steep radio spectrum sources, many of which are likely to be millisecond pulsars or short orbital period binary pulsar systems. Such objects would be used to address such questions as

- **What Are New States of Matter at Exceedingly High Density and Temperature?**
- **Did Einstein Have the Last Word on Gravity?**
- **Is a New Theory of Matter and Light Needed at the Highest Energies?**

LOFAR's enormous leaps in sensitivity at frequencies below 250 MHz and new ways to explore observational phase space will broaden the horizons of the physical universe. In addition to the identifiable contributions to answering the questions summarized above, LOFAR may be expected to discover new phenomena and to prompt new questions.

1. The Low Frequency Array

The Low Frequency Array (LOFAR) is a revolutionary new radio telescope being developed for the 10 to 240 MHz spectral range, with initial operations planned for the 2006–2008 time period. The instrument is fully solid-state, with no moving parts. The primary antenna elements are simple dipoles with multi-steradian field of view, and apertures are synthesized and pointed by delay and combination of digitized signals using high performance digital processors. This design results in extreme agility, and allows the telescope to look in multiple, widely separated directions simultaneously, with full sensitivity in each direction. The array is large (400 km diameter), and far more sensitive than existing telescopes in this frequency range. The principal technical challenges for the project lie in data processing and ionospheric calibration, and in contrast to most conventional telescopes, the total cost is dominated by silicon and software instead of physical collecting area and precision optics. In effect, LOFAR data processing at rates measured in terabits per second amounts to precision digital sampling and reconstruction of the incoming wavefronts from many simultaneous directions, leading to extraordinary possibilities. More details on the nature of LOFAR and its capabilities are provided in the Appendix.

2. Radio Pulses from Ultra-High Energy Particles

Even though cosmic rays were discovered nearly 100 years ago, *Connecting Quarks with the Cosmos* concludes that many of the acceleration details remain poorly understood at best. While cosmic rays less energetic than about 10^{15} eV are generally considered to be accelerated by supernovae in the Galaxy, the acceleration of cosmic rays with energies extending to or beyond 10^{20} eV is enigmatic. Radio astronomy shares with gamma-ray astronomy sensitivity to high-energy cosmic rays. In fact, several classes of cosmic ray sources produce coherent emission in the radio band and these involve, especially in the case of pulsars, acceleration processes that are not well understood. LOFAR will probe particle acceleration over the entire range of known particle energies—from acceleration of Galactic cosmic rays in supernova remnants at energies of order 1 TeV to ultra-high energy cosmic rays with energies potentially exceeding 10^{20} eV. Indeed, this question meshes well with two of the LOFAR key scientific projects (1) Acceleration, Turbulence, and Propagation and (2) The Bursting and Transient Universe.

2.1. Ultra-High Energy Cosmic Rays

LOFAR has a particular contribution to make to the study of ultra-high energy cosmic rays (UHECRs), with energies $E \gtrsim 5 \times 10^{19}$ eV (~ 10 J). As these particles propagate, they should see a low-energy "bath" of cosmic microwave background photons, off which they should scatter and lose energy, which means that we should see few above the Greisen-Zatsepin-Kuzmin (GZK) limit $E \sim 5 \times 10^{19}$ eV. The current understanding is that the mere existence of these particles requires either as-yet-unidentified accelerator(s) fairly nearby ($\lesssim$ 50 Mpc) or unknown massive particles whose decay results in UHECRs. Moreover, UHECRs are anticipated to have counterparts in ultra-high energy neutrinos and extreme energy γ-ray photons. The number of such particles would be small, though, so large detector volumes are required in order to detect reasonable numbers.

A radio telescope can exploit the atmosphere as a huge particle detector. When UHECRs hit the Earth's atmosphere, they produce extensive air showers (EASs) of secondary particles, propagating relativistically toward the ground in thin "pancakes" of order a hundred meters across, but only a meter or two thick. These showers can develop an excess of electrons ($\sim$ 10%), which interact with the Earth's magnetic field to give rise to an intense broadband pulse of highly beamed, coherent emission. These pulses are relatively easy to detect; the first detection was at 44 MHz by Jelley et al. (1965), followed by detections at various frequencies below 1000 MHz by a number of other groups over roughly the next decade. Difficulties in data capture and processing as well as increasing interference from other users of the radio spectrum discouraged development of this technique.

LOFAR will be a powerful instrument for studying UHECR radio pulses, as its planned operating frequency range covers the range over which radio pulses from cosmic rays have been detected, and it possesses ultra-widefield detection and high time resolution capabilities. Although LOFAR will have a large collecting area, raw sensitivity is usually not an issue. UHECR radio pulses are sufficiently strong that the signal-to-noise ratio is not an issue. Rather, the challenge is to achieve useful event rates, because such particles are extremely rare, with rates at the GZK limit estimated at 0.4 km^{-2} yr^{-1}. The particular utility of LOFAR comes from other aspects of its design.

- The approximately 1 km^2 footprint of a pulse means that each LOFAR station samples an effective cross-sectional area of approximately 1 km^2; with approximately 100 such stations spaced by more than 1 km, LOFAR represents a total cross-sectional area of 100 km^2, *provided* the stations are sensitive to signals from any direction.

- LOFAR is a largely digital instrument, so sampling on sub-microsecond time scales is relatively easy to implement. The addition of a data buffer to the signal stream of each antenna provides a "lookback" capability, upon the *ex post facto* identification of a pulse, with the data buffer thereafter available for off-line analysis.

- The digital analysis will permit detailed reconstruction of the incoming wavefront from any direction, and precise characterization of the airshower structure, composition, and parent cosmic ray particle. LOFAR also will utilize advanced algorithms to excise or avoid terrestrially-generated radio frequency interference.

The telescope is expected to be able to detect useful numbers of UHECRs with energies of order 10^{20} eV. If there is an isotropic radio signature, the detection energies may extend above 10^{21} eV, while modest enhancements such as a simple array of co-located particle detectors could probe the chemical composition of the cosmic rays.

2.2. Ultra-High Energy Neutrinos

Connecting Quarks with the Cosmos notes that high-energy neutrinos should also be generated in the processes that generate UHECRs. These high-energy neutrinos can produce radio pulses when they strike the lunar regolith. Searches for such radio pulses have been carried out (Hankins et al. 1996). None were detected, implying either that the maximum energy in high-energy neutrinos is roughly 7×10^{19} eV or that the flux of higher energy neutrinos is at least an order of magnitude lower than expected.

LOFAR can contribute to searches for lunar neutrino pulses. The predicted radio spectrum of these pulses scales as ν, but the loss tangent of the lunar regolith should scale as ν^{-1} so that they suffer less absorption at lower frequencies. To first order, the radio emission from lunar neutrino pulses should therefore be frequency independent. Moreover, the field of view of LOFAR is larger than the Moon itself, in contrast to the existing searches which have been able to view only a fraction of the Moon. By viewing the entire surface of the Moon, the effective detector volume could be as large as 10^{13} m^3 ($= 10^4$ km^3), much larger than can be obtained with terrestrial detectors.

Results from LOFAR are expected to complement those from optical Cerenkov detectors such as the Southern Auger facility and anticipated space detectors of atmospheric events. Although we have focused on LOFAR's capabilities for addressing this question, LOFAR and the even larger scale Square Kilometer Array (SKA) should complement each other nicely in studying lunar neutrino pulses.

3. The Epoch of Reionization, Structure Formation, Dark Matter, and Dark Energy

Connecting Quarks with the Cosmos describes how the work of Zwicky provided early evidence for a kind of matter that does not interact with photons—dark matter. Over the past 30 yrs that evidence has been growing stronger, based on such diverse observations as galaxy rotation curves, cluster lensing observations, and observations of the cosmic microwave background. Although some dark matter has been identified (neutrinos are a form of hot dark matter), it is not enough to explain the observations; additional, cold dark matter is required for detailed agreement with the observations.

More recently, observations of distant Type Ia supernovae indicate that the expansion of the Universe is accelerating, suggesting the presence of a repulsive component of gravity. Observations of fluctuations in the cosmic microwave background also indicate that the Universe's composition includes a repulsive gravitational or negative pressure component. A variety of candidates to explain this *dark energy* exist, ranging from the classical cosmological constant introduced by Einstein to more recent suggestions of the energies of the quantum vacuum and evolving scalar fields.

One promising avenue for probing the properties of both dark matter and dark energy is via their effects on *structure formation*, in particular by identifying the first structures, the first stars and galaxies. LOFAR will also be a superb instrument for studying clusters of galaxies in its own right, expected to reveal hundreds or even thousands of new radio relics and halos easily. The study of these objects will contribute significantly to our understanding of the evolution of large scale structure over cosmic time.

3.1. Dark Matter

Both the distribution and properties of dark matter influence the formation of the first stars. The distribution of dark matter is important because the structures observed today are far larger than can be accommodated if only luminous matter is responsible for their formation. Thus, it must be the formation of dark matter halos that provides the "seeds" from which stars, galaxies, and clusters have been assembled. The relative ratio of hot and cold (and possibly warm) dark matter determines the scale sizes of the initial structures. Cold dark matter tends to produce initial structures of a relatively smaller size, while hot dark matter tends to smooth out the "lumpiness" of initial structures, producing relatively larger scale sizes.

The hydrogen atom has a hyperfine transition that produces radiation at a frequency of 1420 MHz. In order for the first stars and galaxies to form, the luminous matter in the Universe (mostly hydrogen) had to condense and cool into the dark matter halos. The condensation and cooling could excite this hyperfine transition. Moreover, the first stars are thought to have been fairly massive ($\sim 100\ \mathrm{M}_\odot$) due to the relative difficulty that a hydrogen-helium gas has in cooling. (The hyperfine transition of hydrogen is a fairly poor cooling mechanism compared to the fine-structure transitions in the ground states of heavier elements, none of which had been formed yet.) These first stars were likely to have been efficient producers of ionizing photons, so that after they had formed they would begin to ionize their surroundings. Thus, immediately after the first stars formed, the Universe would have consisted of a patchwork of neutral and ionized hydrogen. Analysis of observations by the *Wilkinson Microwave Anisotropy Probe* indicates that this reionization process occurred at redshifts $z \approx 15 \pm 5$. Detection of the Gunn-Peterson trough in quasars from the Sloan Digital Sky Survey suggests that this reionization process did not conclude until $z \simeq 7$.

The redshifted emission and/or absorption from hydrogen just prior to and during the epoch of reionization should therefore be in the frequency range of approximately 180 MHz ($z \simeq 7$) to 70 MHz ($z \simeq 20$). Detection of this redshifted hydrogen transition from the epoch of reionization forms one of the key scientific projects for LOFAR.

Detecting the hydrogen signal from the epoch of reionization would enable study of the first structures when they are (largely) in the linear regime of gravitational clustering, where the comparison with both analytical theory and simulations is much more straightforward. After non-linear gravitational clustering has taken place, the situation is made far more difficult by the gas dynamics of star formation and its associated feedback mechanisms (e.g., winds from early supernovae can disrupt later nascent star formation) as well as biasing.

In effect, LOFAR observations have the possibility for observing what are considered to be the "initial conditions" of structure formation, providing important constraints on the properties of dark matter.

3.2. Dark Energy

In general relativity, gravitational effects are determined by $(\rho + 3p)$ terms, where ρ is the energy density of the component (baryonic matter, dark matter, dark energy) and p is its pressure. Baryonic matter and (presumably) dark matter both produce a positive pressure and energy density. In contrast, dark energy has a negative pressure. If $p \leq -\rho/3$, so that the term $(\rho{+}3p) < 0$, then the gravitational effects of dark energy become repulsive, working to accelerate the Universal expansion.

A key open question regarding dark energy is its *equation of state*, which is typically parameterized as $p = w\rho$. It is not yet clear whether w, and therefore the negative pressure exerted by dark energy, may evolve with cosmic epoch (i.e., redshift). The classical cosmological constant is described by a constant $w(z) = -1$.

LOFAR contributes to dark energy studies through analysis of the growth of structure from near or before the epoch of reionization ($z \sim 10$) to the current time ($z \approx 0$). LOFAR will measure fluctuations in the redshifted hydrogen emission at scales of several tens of Megaparsecs and larger, where the fluctuations are linear and it is possible to measure directly the linear power spectrum. This measurement will then place significant constraints on the cosmic equation of state, because it probes the growth of linear fluctuations from redshifts of about 10 to the present time. The growth of fluctuations is strongly dependent on the expansion rate of the universe and so on the cosmic equation of state.

Figure 1 illustrates joint constraints that can be placed on the first and second derivatives of the equation of state of the dark energy (i.e., w) by measuring the amplitude of the linear matter power spectrum at $z \sim 10$ with 10% (blue area) and 3% (red area) precision. A measurement with LOFAR is expected to achieve about 3% precision in a reasonable integration time.

4. Other Questions

LOFAR will also play a role, though perhaps not a central one, in answering additional questions.

By virtue of its large field of view, LOFAR will be an extraordinarily efficient survey instrument. Consequently, imaging surveys with LOFAR will identify detect numerous steep-spectrum sources, including many pulsar candidates. Radio pulsars are the most numerous of the known classes of

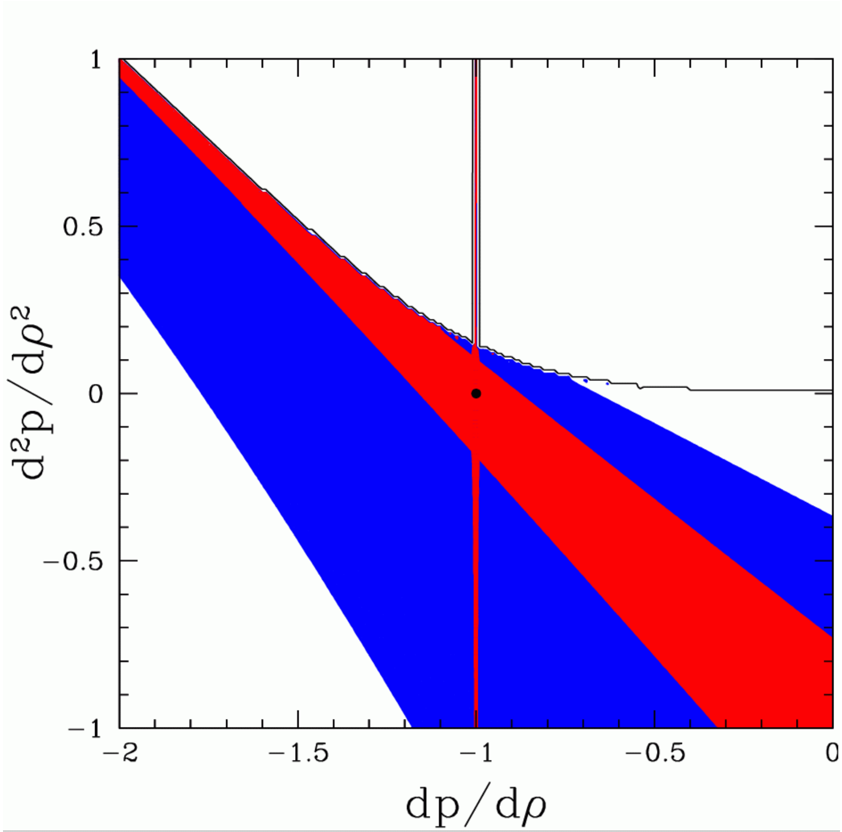

Fig. 1.— The joint constraints that can be placed on the first and second derivatives of the equation of state of the dark energy by measuring the amplitude of the linear matter power spectrum at $z = 10$ with 10% (blue area) and 3% (red area) precision. The black dot is the standard LCDM model. The black line is the boundary beyond which there is no Universe that exists at $z = 0$ and $z = 10$. The vertical line indicates $w = -1$. (Figure courtesy of N. Gnedin.)

neutron stars. With their extreme densities ($\gtrsim 10^{14}$ g cm^{-3}) and high magnetic fields (with some neutron stars having fields in excess of 10^{13} Gauss), neutron stars provide a ready environment for probing physics in extreme environments. Any new classes of neutron stars are evidently either rare or manifest themselves in regions of observational phase space that have not yet been probed to the necessary degree of completeness. In particular, it is significant that the shortest period pulsars known have steep radio spectra. Also, it is known that there are serious selection effects against short-orbital period pulsar binaries in the current pulsar census. Steep-spectrum objects detected by LOFAR could be searched for pulsations with the Arecibo Observatory, the GBT, the SKA, or other telescopes to reveal objects of these types. Thus, searches for steep-spectrum objects and pulsar studies with LOFAR could address three questions:

What Are the New States of Matter at Exceedingly High Density and Temperature?

Recently, particular neutron stars have been recharacterized as quark or strange stars. Though such claims are not overly compelling at present, they underscore the possibility that new kinds of stellar objects may be discovered in LOFAR steep-spectrum surveys, enabling the identification (or ruling out) of more exotic states of matter.

Did Einstein Have the Last Word on Gravity?

General Relativity has not been tested in the strong gravity regime, and it has not been modified to include quantum mechanical effects. LOFAR steep-spectrum surveys could identify short-orbital period pulsar-black hole binaries that could be monitored in exquisite detail to probe relativistic effects and spacetime around black holes.

Is a New Theory of Matter and Light Needed at the Highest Energies?

It is not understood how the quantum critical field B_q ($= 4.4 \times 10^{13}$ Gauss) plays a role in the electrodynamics of a neutron star's magnetosphere. Both surveys and analyses of particular objects will provide a window for answering this question.

In addition, mapping of neutron stars' magnetic fields is highlighted as an outcome of future X-ray polarimeters. Such mapping has been conducted for many years on radio pulsars using polarimetric techniques. It is fair to say, however, that comprehensive, three-dimensional mapping of magnetic fields has not been done. Arguments are often made that different radio frequencies arise from different altitudes in pulsar magnetospheres. Alternative pictures apply as well, but it is plausible that different frequencies sample different parts of the magnetosphere. With existing telescopes, sufficient telescope time has not been available to measure polarization over a large dynamic range in frequency. On nearby objects, LOFAR will be able to extend the range by another factor of 10 or so. The interpretation of such measurements is undoubtedly complicated but rich possibilities for mapping the magnetic fields surely exist. A byproduct of such analyses may also be constraints on neutron star radii, because the radius sets the scale of the dipolar component of the magnetic field.

Finally, a fourth question that LOFAR will address is

Are There Additional Space-Time Dimensions?

Various attempts to unify the standard model of particle physics with general relativity suggest that there may be additional spacetime dimensions, which would imply that various physical constants are not, in fact, constant. Radio astronomical observations have already placed austere limits on the possible variation of physical constants such as the fine structure constant α and the gravitational constant G. For example, Carilli et al. (2000) used the 1.4 GHz hyperfine transition of neutral hydrogen at various redshifts to place a constraint on the fine structure constant of $\dot{\alpha}/\alpha < 3.5 \times 10^{-15}$ yr^{-1}, with attendant limits on the possible evolution of compacted dimensions. By comparison Murphy et al. (2002) suggest that $\dot{\alpha}/\alpha = (6.40 \pm 1.35) \times 10^{-16}$ yr^{-1}.

In combination with radio telescopes operating at higher frequencies (e.g., the VLA, Arecibo, GBT, and the SKA), LOFAR will probe the 1.4 GHz hyperfine transition of H I to redshifts potentially as large as $z \approx 20$, as well as simply providing many more systems to use for placing constraints. This would enable far stronger conclusions about the variability of α.

5. Future Questions

Discoveries in radio astronomy have led to many of the current concepts of the Universe, in many cases through fortunate accidents resulting from technological extensions to new domains of frequency and sensitivity. The history of radio serendipity started with the discovery of cosmic radio emission itself, found as a by-product of the hunt for sources of static in radio communications with a high sensitivity antenna. Solar radio emission, Jupiter's decameter emission, radio galaxies, quasars, the cosmic microwave background, and pulsars were all accidental discoveries in the first or early results from new telescopes or systems. The "greenhouse effect," perhaps the most practically important concept in 20^{th} Century geophysics, was first detected in the anomalously high surface temperature of Venus found with a new, centimeter-wavelength telescope.

LOFAR's vast improvements in the sensitivity and resolution available at low frequencies will provide at least as much of a new view of the Universe as the improvements that led to the prior great discoveries of radio astronomy. LOFAR's principal scientific justification is to open up this new view, both of the different physical mechanisms that are manifest at low radio frequencies and of the various transient phenomena in the radio Universe. Indeed, while LOFAR has specific key scientific goals, and while LOFAR will be able to address a number of the specific fundamental physics questions in the *Connecting Quarks to the Cosmos* report, a key objective of its design is to provide an exploration machine with sufficient power to yield new, as yet unimagined perspectives. LOFAR will be flexible enough to address both the questions of today and the questions of the future.

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A. What is LOFAR?

The Low Frequency Array (LOFAR) will be a radio telescope array operating between 10 and 240 MHz, with a total collecting area of 10^6 m^2 (= 1 km^2) at a frequency of 15 MHz. Table 1 summarizes its design goals.

Table 1: LOFAR Basic Specifications

Parameter		Design Goal
Frequency Range	Low	10–90 MHz[a]
	High	110–240 MHz
Redshift Coverage (H I)		> 4.9
Number of Receptors	Low (10–90 MHz)	13,365 dipoles
	High (110–240 MHz)	213,840 dipoles
Configuration	Virtual Core (VC, 25% collecting area)	$\lesssim 2$ km
	Extended Array	400 km
Baselines		0.02–400 km
Highest Angular Resolution (FWHM)		$0\farcs64$ at 240 MHz
Antenna Field of View		4 steradian
Imaging Field of View		~ 1–25 deg^2

[a]LOFAR may include the 90–110 MHz band.

The basic elements—individual dipoles in the 10–90 MHz band and small dipole arrays in the 110–240 MHz band—will be grouped into approximately 100 "stations" (each the equivalent of a parabolic antenna in a centimeter-wavelength array). The stations will be distributed over an effective aperture of 400 km, in an array configuration that is roughly scale-free, to provide a wide range of resolutions and surface brightness sensitivities, thereby serving a wide variety of scientific applications. Figure 2 shows a schematic of how LOFAR might look eventually, based in part on prototype work in progress.

Figure 3 illustrates that the combination of large collecting area and long baselines results in LOFAR having a sensitivity and resolution that is orders of magnitude better than previous and existing telescopes in this frequency range. The long baselines of LOFAR are particularly essential as they produce high angular resolution, thereby reducing source confusion which has been a fundamental problem with most previous low-frequency radio telescopes. The efficacy of this has been clearly demonstrated by pioneering work at 74 MHz with the 35-km VLA, which has led to dramatic gains in sensitivity even with only limited collecting area. In order to utilize fully the long baselines, new approaches to ionospheric calibration are being developed for LOFAR, which as a byproduct will provide ionospheric measurements of unprecedented precision, spatial density, and temporal resolution.

LOFAR will exploit the improvements in electronics technology over the past few decades so that fast sampling and novel signal processing schemes will be relatively easy to implement. Signals

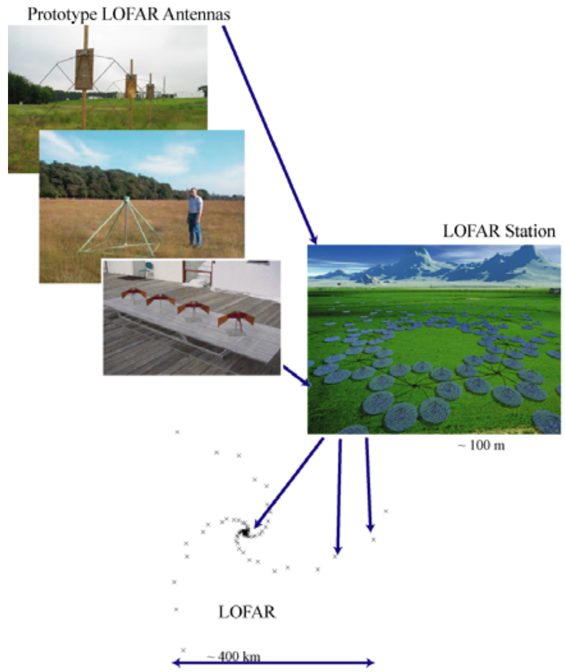

Fig. 2.— A LOFAR schematic. The individual receptors are dipoles, and prototype dipoles are shown in the upper left. Shown are both "low-band" (10–90 MHz) prototypes and "high-band" (110–240 MHz) prototypes. The individual dipoles are joined in "stations," each of which is equivalent to a parabolic dish antenna in a centimeter-wavelength array. Individual stations form the outer portion of the LOFAR network, while the "virtual core" is composed of approximately 3000 antennas in a relatively compact configuration over a 2 km region.

from the dipoles or dipole arrays will be digitized immediately and transformed to the frequency domain. At each station, multiple simultaneous phased array beams will be formed on the sky, and the resulting data will be transported via optical fiber to a central processing facility for cross-correlation, calibration and imaging. Approximately 25% of the stations will be grouped into a central region in the inner 2 km of the array, the virtual core (VC). Within the VC, the dipoles and dipole arrays will be configured for more flexible processing of the signals.

Key features of LOFAR of relevance to the *Connecting Quarks with the Cosmos* questions are:

- High sensitivity, permitting the detection and study of a wide range of astronomical sources and phenomena;
- Multibeaming capability, permitting long-duration experiments to be conducted without severe competition from other users, as well as simultaneous observation of large numbers of objects (such as pulsars) with full sensitivity;
- A per-antenna data buffer, allowing for post-facto observing of sources in any direction upon

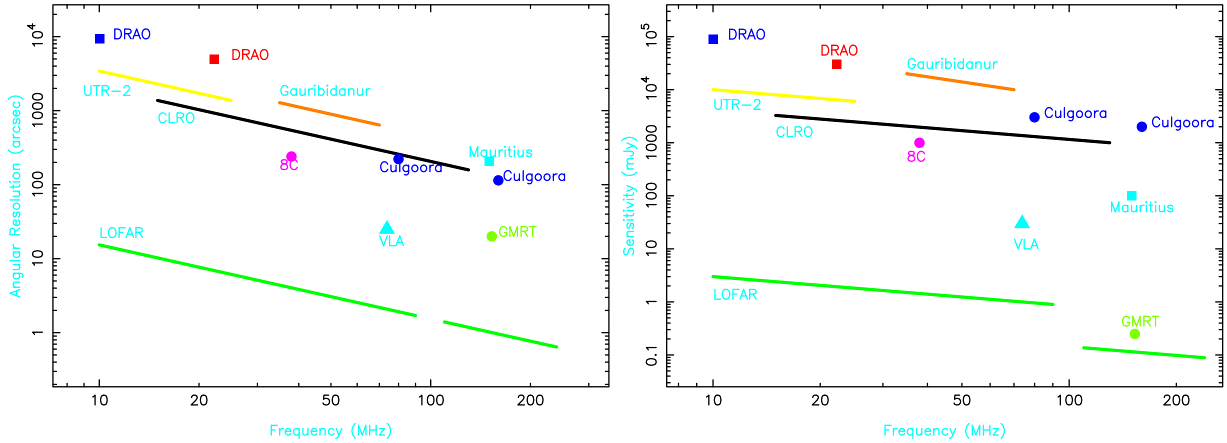

Fig. 3.— *Left* Angular resolution (arcseconds) as a function of frequency for past and present imaging instruments and LOFAR. The various telescopes include the UTR-2, Gauribidanur, 8C, Clark Lake Radio Observatory (CLRO), Culgoora, Dominion Radio Astrophysical Observatory (DRAO), the Mauritius radio telescope, and the 74 MHz VLA. The Giant Metrewave Radio Telescope is shown, though its capability at 150 MHz has not been implemented fully yet. For LOFAR, the break between 90 and 110 MHz occurs as a result of the switch from single dipoles to dipole clusters within a station. Also, it is possible that frequency coverage of the low-frequency dipoles may extend up to 110 MHz eventually. *Right* Sensitivity (mJy) to a point source as a function of frequency. The sensitivities are estimates of the minimum detectable flux density provided by past and present telescopes. For LOFAR, we show the expected sensitivity for a single polarization in a 1 hour integration with a 4 MHz bandwidth.

receipt of a trigger signal; and

- Extreme pointing and frequency agility, with response times measured in milliseconds, a consequence of the complete lack of moving parts in LOFAR.

LOFAR is being designed and developed by the Massachusetts Institute of Technology/Haystack Observatory, the Netherlands Foundation for Research in Astronomy (ASTRON), and the US Naval Research Laboratory (NRL).

The science case for LOFAR is available elsewhere[1] and is still evolving, as is to be expected from a facility that is designed to target a number of forefront science areas. It will also be discovery instrument through its expansion of observational phase space in key ways (frequency range, solid angle, time resolution, and modes of operation). Five key scientific projects have been identified for LOFAR

Epoch of Reionization Attempt to detect the Universe's transition from neutral to largely ionized, which the Wilkinson Microwave Anistropy Probe (WMAP) results suggest happened in

[1]See http://www.lofar.org/, and http://lofar.nrl.navy.mil/.

the redshift range $z \approx 15 \pm 5$, and characterize the power spectrum of matter fluctuations at the time of the transition.

The High-Redshift Universe Search for high-redshift radio galaxies. As these are thought to be powered by supermassive black holes, finding radio galaxies at ever higher redshifts places constraints on the mechanisms by which galaxies and supermassive black holes can assemble themselves.

Acceleration, Turbulence, and Propagation Probe the three-dimensional distribution of electrons, magnetic fields and cosmic rays throughout the Milky Way, and determine their role in the generation and dissipation of turbulence, the propagation of radiation, and the acceleration of high-energy particles.

The Bursting and Transient Universe Conduct an unbiased survey of the sky for radio transients.

Space Weather and Ionospheric Physics At low frequencies, radio waves carry information about their propagation, which will be used as an exquisite probe of the near-Earth environment. As a receiver for resolving reflections of radar transmissions off of Earth-ward bound coronal mass ejections (CMEs), LOFAR can open a new field of solar physics and space weather studies.

Combined with the suite of existing national radio facilities (Arecibo, GBT, VLA), other near-future instruments (ATA, EVLA, and ALMA) and next-decade telescopes (SKA), LOFAR will advance our knowledge of basic physics and broaden the horizons of the physical (and biological) universe.

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